Production of Strange Clusters and Strange Matter in Nucleus-Nucleus Collisions at the AGS

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Abstract

Production probabilities for strange clusters and strange matter in Au+Au collisions at AGS energy are obtained in the thermal fireball model. The only parameters of the model, the baryon chemical potential and temperature, were determined from a description of the rather complete set of hadron yields from Si+nucleus collisions at the AGS. For the production of light nuclear fragments and strange clusters the results are similar to recent coalescence model calculations. Strange matter production with baryon number larger than 10 is predicted to be much smaller than any current experimental sensitivities.

In a recent study [1] of thermal equilibration and expansion in nucleus-nucleus collisions at AGS energies we have shown that a consistent description of the production of hadrons in Si-nucleus collisions can be obtained under the assumption that strangeness is completely equilibrated. Here we explore the predictions of this thermal model with respect to the formation of light nuclear fragments and strange clusters and focus, in particular, on production probabilities of strange matter in Au+Au collisions at AGS energy.

The possibility that matter composed of a roughly equal mixture of up-, down-, and strange quarks is metastable or even stable has been a subject of intense recent investigations.

An introduction and comprehensive survey of experimental and theoretical considerations can be found in [2]. A number of experimental searches are currently underway to test the possible existence and (meta)stability of this new phase of matter. Since strange quark matter has a very large strangeness to baryon number ratio [3] of $|S|/B \approx 0.8$, most of the searches focus on ultrarelativistic nucleus-nucleus collisions, where significant numbers of strange particles can be produced per interaction. In fact, at AGS energies, strangeness production as measured by the probability $\lambda = \frac{2s\bar{s}}{u\bar{u}+d\bar{d}}$ is enhanced compared to that found in nucleon-nucleon collisions by about a factor of two [4,5].

In the present investigation we use a fireball model based on the assumption of thermal and chemical equilibrium to make predictions for strange matter production probabilities in such collisions. The success of this model reported in [1] suggests that, at AGS energies, thermal and chemical equilibrium are, indeed, achieved. Within such a thermal model, particle production does not anymore depend on specific (and, in general, unknown) cross sections but rather is governed by conservation laws and the baryon chemical potential and temperature of the system at freeze-out, as well as by the mass and quantum numbers of the particle to be produced. The success of the model for strangeness production in general implies that the present estimates should provide a baseline for strange matter production from hadronic matter at freeze-out. Whether quark-gluon plasma formation and subsequent hadronization can lead to strange matter production which is enhanced beyond the present estimate which is based on chemical equilibration is unclear at present.

As shown in [1] the available data on hadron yields in central Si-nucleus collisions at 14.5 GeV/c per nucleon can be quantitatively described in a fireball model under the assumption of thermal and chemical equilibrium. In this model, the particle number densities are given as integrals over particle momentum p:

$$\rho_i^0 = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_b B_i - \mu_s S_i)/T] \pm 1} \tag{1}$$

where g_i is the spin-isospin degeneracy of particle i, E_i, B_i and S_i are its total energy in the local restframe, baryon number and strangeness, and μ_b and μ_s are the baryon and

strangeness chemical potentials ($\hbar$=c=1). As in [1] we employ finite and excluded volume corrections. Analysis of the Si-nucleus data yields a value of $\mu_b = 0.54$ GeV and a temperature range of $0.12 < T < 0.14$ GeV. For a given temperature and baryon chemical potential the strangeness chemical potential μ_s is fixed by strangeness conservation. In particular, for $T = 0.120$ and 0.140 GeV one obtains $\mu_s = 0.108$ and 0.135 GeV. This thermal approach leads to a good description of all strange particle yields measured so far at AGS energy [1].

In Table I we show that the model for Si+Pb collisions also very well reproduces the measured d/p and $\bar{\text{d}}/\bar{\text{p}}$ ratios, without explicit reference to the underlying coalescence mechanism which presumably governs the production of such loosely bound clusters. To explore the thermal model predictions for more complex clusters we have also calculated production probabilities in central Au-Au collisions for ordinary and (multi)-strange clusters recently discussed in ref. [6]. The results are shown in Table II. To compute absolute production probabilities one has, of course, to specify a freeze-out volume. We have chosen this volume such that the total pion multiplicity (charged and neutral) is 450 for central Au-Au collisions, in accord with preliminary data from experiment E866 [8]. The corresponding freeze-out volume is 2600 and 5000 fm^3, for $T = 0.14$ and $T = 0.12$ GeV, respectively, quite reasonable in view of the recent estimate for the freeze-out volume from Si+Pb collisions [9]. An alternative possibility would have been to fix the number of baryons in the fireball to 394, leading to very similar results. As shown in Table II the thermal model predicts deuteron, t, ^{3}He, and α particle production in close agreement with results from the coalescence model. This latter fact is particularly relevant in connection with thermal model predictions of strange matter production since strange matter is predicted [12] to have similar central density as ^{4}He. The results for strange cluster production are also compiled in Table II. They agree rather well with the coalescence model calculations reported in [6], lending support to the conclusion that such clusters, should they exist as (quasi)bound states, should be observable in Au+Au collisions at AGS energy. Close inspection of Table II reveals that the coalescence model of [6] predicts somewhat larger production probabilities compared to the thermal model for multistrange clusters with baryon number larger than 4.

The origin may be the particular choice of the coalescence parameters [7]. We stress again that only the baryon number, mass, spin and strangeness of the cluster enters the thermal model calculation here and the results are independent of particular cluster wave functions and coalescence parameters.

To compute production probabilities for strange matter clusters (or strangelets) we use the Berger and Jaffe [3] mass formula to determine the most stable charge and strangeness of a cluster with given baryon number B. For the energy per baryon of each cluster we use the recent mass formula of [13], where curvature and surface effects are properly calculated for small clusters. Using the total energy, baryon number, and strangeness we are now in a position to estimate the strangelet production in central Au-Au collisions at AGS energy. The results are again listed in Table II. Even for the $^{10}_{1}$St^{-8} strangelet with baryon number 10, charge number 1, and strangeness $S = -8$, which is predicted to be unstable against strong decays [13], the production probability is less than 10^{-12} per central Au-Au collision. For each increase in baryon number by one, one has to pay a penalty factor of the order of $\exp(-\Delta m/T)\exp((\mu_b - \mu_s)/T)$, where Δm is the corresponding increase in strangelet mass. This amounts to about a factor 50 and 70 for $T = 0.14$ and $T = 0.12$ GeV, respectively. Note that, in our model, even ordinary nuclei with baryon number larger than 10 are only produced at minute rates in central Au+Au collisions: for ^{12}C production at $T = 0.14$ GeV we predict a production probability of $5.4 \cdot 10^{-11}$ per central Au-Au collision. This should be compared with a production probability of $1.7 \cdot 10^{-15}$ for a strangelet with baryon number $B = 12$ (see Table II). Our calculations produce results which are many orders of magnitude smaller than the predictions by [14], where a specific quark matter production scenario is invoked to estimate strange matter production. Furthermore, the authors of [14] used a much more optimistic mass formula. In the present model, a reduction in strangelet mass by an amount δm, keeping all other parameters fixed, increases the production probability by about $\exp(\delta m/T)$. The uncertainty in strangelet mass consequently leads to a substantial uncertainty in the production probability. However, even the most optimistic scenario for strangelet mass (*i.e.* assuming a bulk binding parameter of 0.88 GeV as in [14]) increases

the production probability for *e.g.* the $^{12}_{1}\text{St}^{-9}$ strangelet from $1.7 \cdot 10^{-15}$ to $2.7 \cdot 10^{-13}$, still below the sensitivity of any existing or proposed experiment.

The thermal model employed here describes all available data on strange and nonstrange hadron production in Si-nucleus collisions at AGS energy, without need to discuss specific reaction mechanisms. Since thermal and chemical equilibrium are the major ingredients of our model, all indications are that it will be applicable also for Au+Au collisions. It should be investigated whether models such as the strangeness distillation scenario proposed in [15] and invoked in [14], where locally more strangeness is produced than in a fully equilibrated hadron gas at freeze-out, correctly predict present data on strange hadron production. We note that, for the quark gluon plasma, the strangenes suppression factor λ is indeed large when calculated in a thermal model, but decreases significantly during hadronization [5].

In conclusion, the fireball model based on thermal and chemical equilibrium describes cluster formation well, where measured. It gives results similar in magnitude to the predictions of the coalescence model developed recently [6] to estimate production probabilities for light nuclear fragments (p, d, t, α ...) and for for strange hadronic clusters (such as the H dibaryon) in Au-Au collisions at the AGS. Predicted yields for production of strange matter with baryon number larger than 10 are well below current experimental sensitivities.

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TABLE I. Particle ratios calculated in a thermal model for two different temperatures, baryon chemical potential μ_b= 0.54 GeV and strangeness chemical potential μ_s such that overall strangeness is conserved, in comparison to experimental data (with statistical errors in parentheses) for central collisions of 14.6 A GeV/c Si + Au.

Particles	Thermal Model		Data		
	T=.120 GeV	T=.140 GeV	exp. ratio	rapidity	ref.
d/(p+n)	$4.3 \cdot 10^{-2}$	$5.8 \cdot 10^{-2}$	$3.0(3) \cdot 10^{-2}$	0.4 - 1.6	[10]
$\bar{\text{d}}/\bar{\text{p}}$	$1.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-5}$	$1.0(5) \cdot 10^{-5}$	2.0	[11]

TABLE II. Produced number of nonstrange and strange clusters and of strange quark matter per central Au+Au collisions at AGS energy, calculated in a thermal model for two different temperatures, baryon chemical potential $\mu_b = 0.54$ GeV and strangeness chemical potential μ_s such that overall strangeness is conserved. The coalescence model predictions are from Table 2 of [6].

Particles	Thermal Model		Coalescence Model
	$T=.120$ GeV	$T=.140$ GeV	
d	15	19	11.7
$t+^3\text{He}$	1.5	3.0	0.8
α	0.02	0.067	0.018
H_0	0.09	0.15	0.07
$^5_{\Lambda\Lambda}\text{H}$	$3.5 \cdot 10^{-5}$	$2.3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
$^6_{\Lambda\Lambda}\text{He}$	$7.2 \cdot 10^{-7}$	$7.6 \cdot 10^{-6}$	$1.6 \cdot 10^{-5}$
$^7_{\Xi^0\Lambda\Lambda}\text{He}$	$4.0 \cdot 10^{-10}$	$9.6 \cdot 10^{-9}$	$4 \cdot 10^{-8}$
$^{10}_{1}\text{St}^{-8}$	$1.6 \cdot 10^{-14}$	$7.3 \cdot 10^{-13}$	
$^{12}_{1}\text{St}^{-9}$	$1.6 \cdot 10^{-17}$	$1.7 \cdot 10^{-15}$	
$^{14}_{1}\text{St}^{-11}$	$6.2 \cdot 10^{-21}$	$1.4 \cdot 10^{-18}$	
$^{16}_{2}\text{St}^{-13}$	$2.4 \cdot 10^{-24}$	$1.2 \cdot 10^{-21}$	
$^{20}_{2}\text{St}^{-16}$	$9.6 \cdot 10^{-31}$	$2.3 \cdot 10^{-27}$	